Launch Vehicle Aerodynamics Database Development for SLS

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NASA Advanced Supercomputing Division (ARC/TNA)

Advanced Modeling & Simulation (AMS) Seminar

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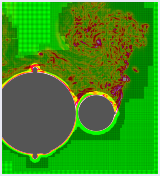
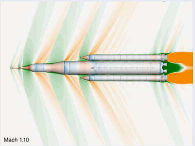
Launch Vehicle Aerodynamics

Wide range of conditions

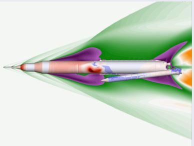
Ground winds



Incompressible

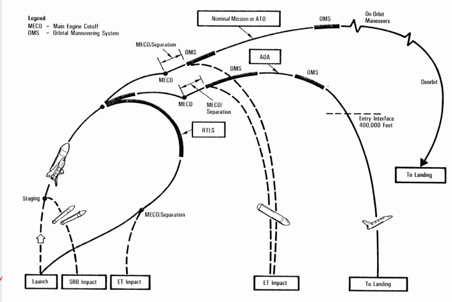


Transonic



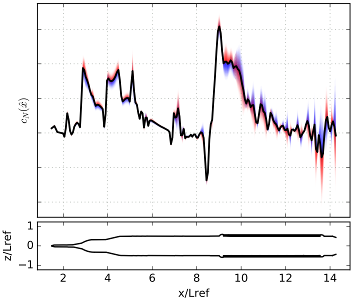
Separation events

Abort scenarios



Abort and Normal Mission Profile

Increased role of uncertainty

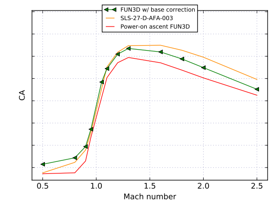


Ascent Aerodynamics

A Multipurpose CFD Setup: 1311 Sims for 4 Databases

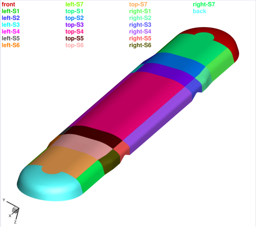
Ascent F&M

- How does the vehicle fly?
- CFD is a supplement to wind tunnel



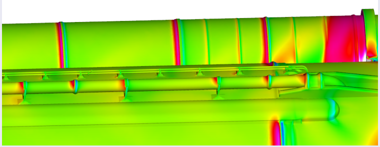
Protuberance Air Loads

- Do parts fall off the rocket?
- Do any parts break?



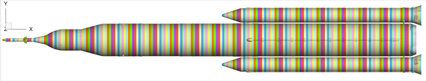
Surface Pressures

- Venting: any parts burst/crush?
- Other uses for surface pressures



Line Loads

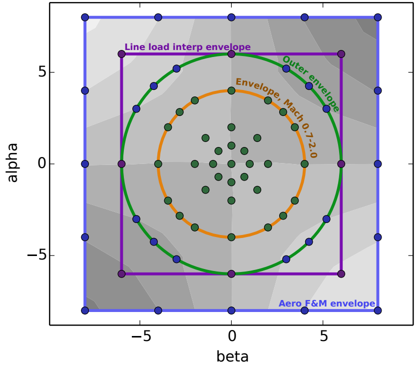
- Does the vehicle break?
- How much does it bend?

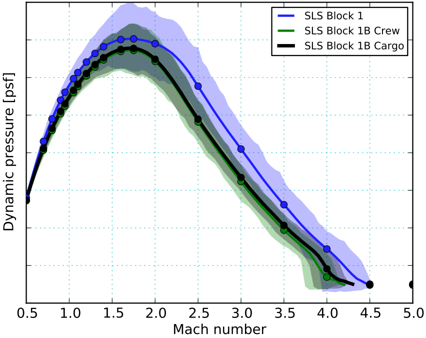


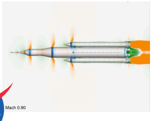
Ascent Aerodynamics Run Matrix: Mach 0.5 to 5.0

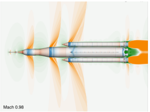
. . . from roughly sea level to very high dynamic pressure to near vacuum

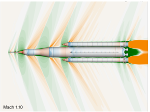
Simulate out to $\alpha = \pm 8^\circ$, even though flight is mostly close to 0

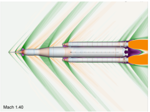


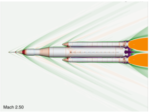


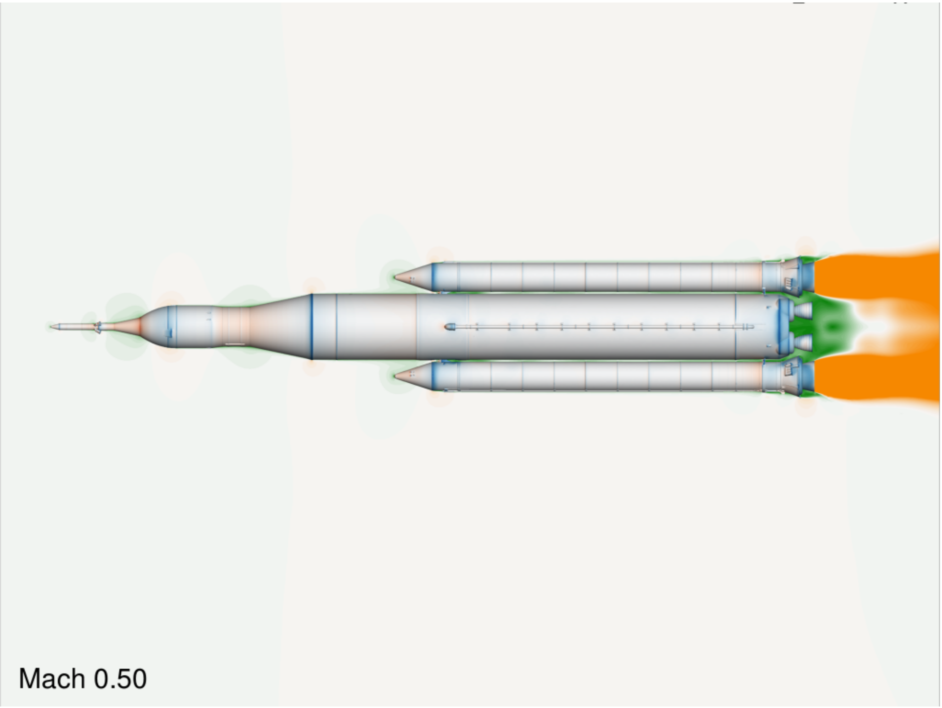


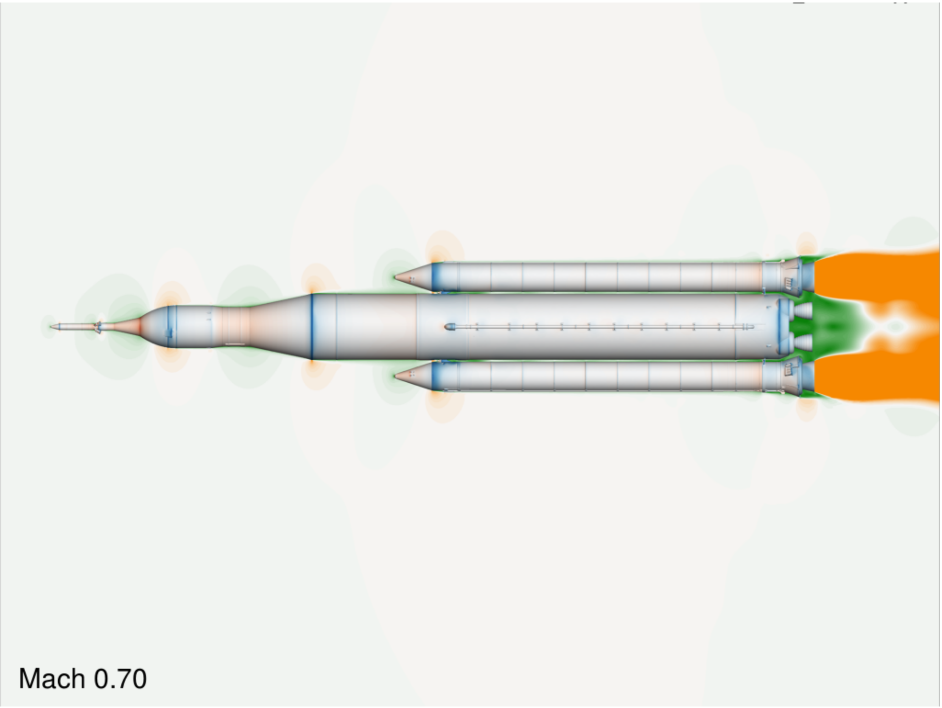




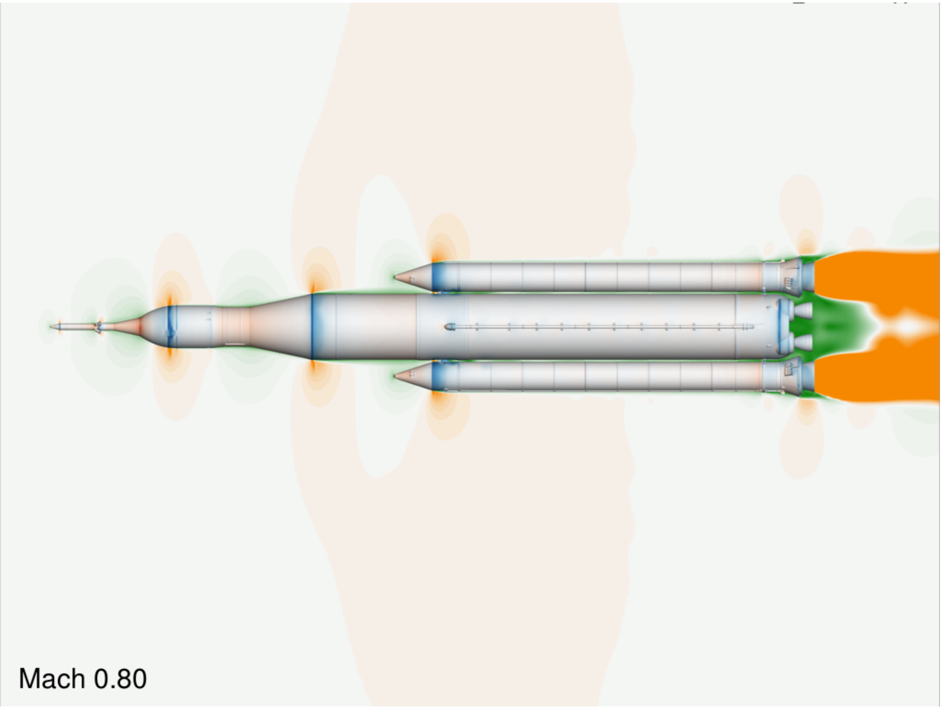


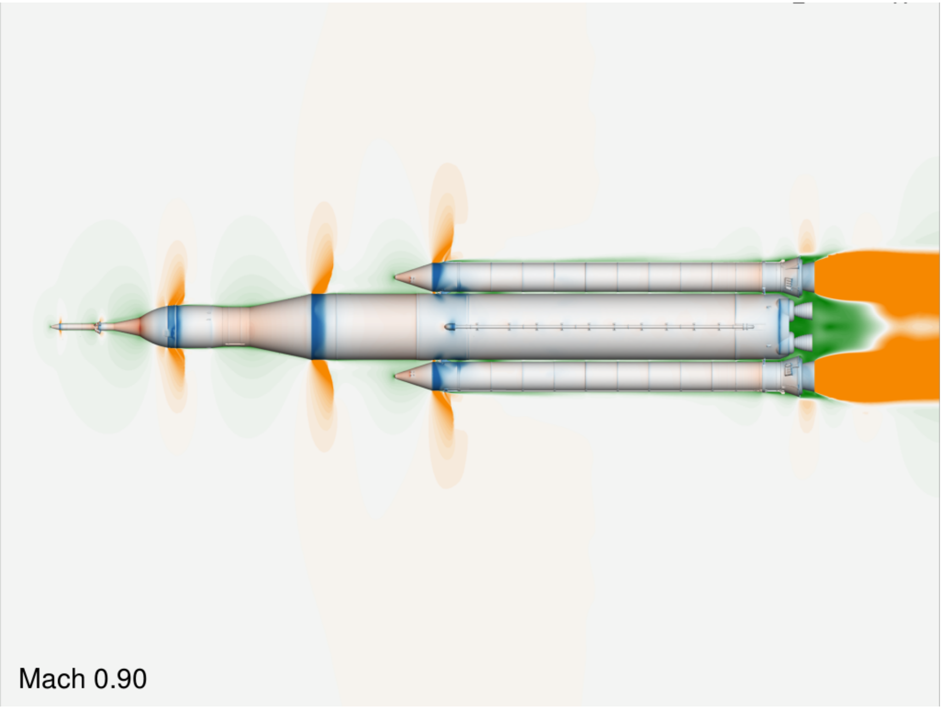


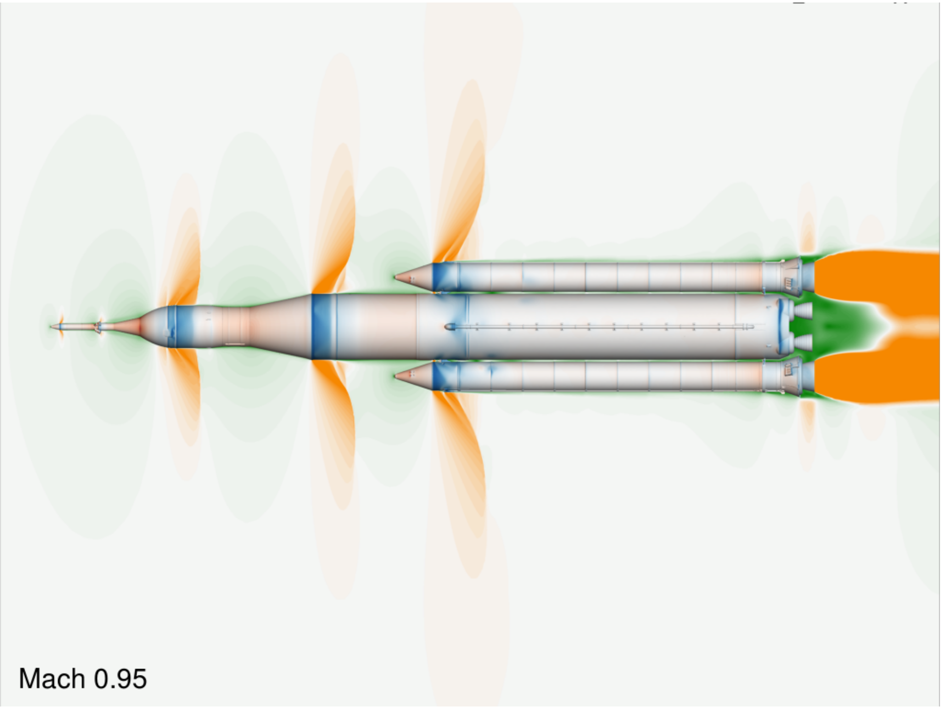

Mach 0.50

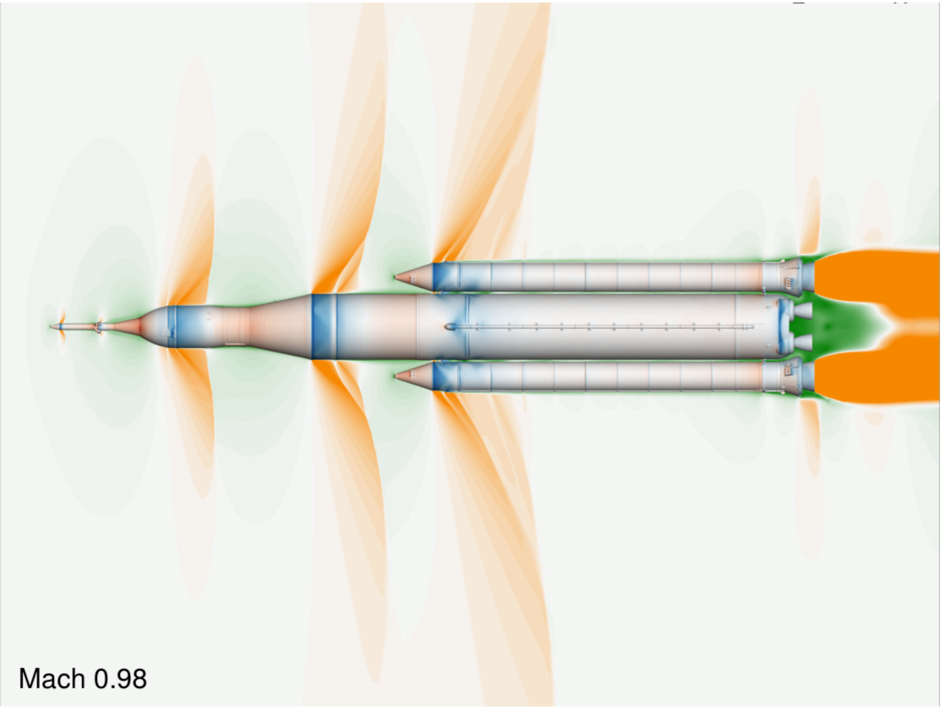


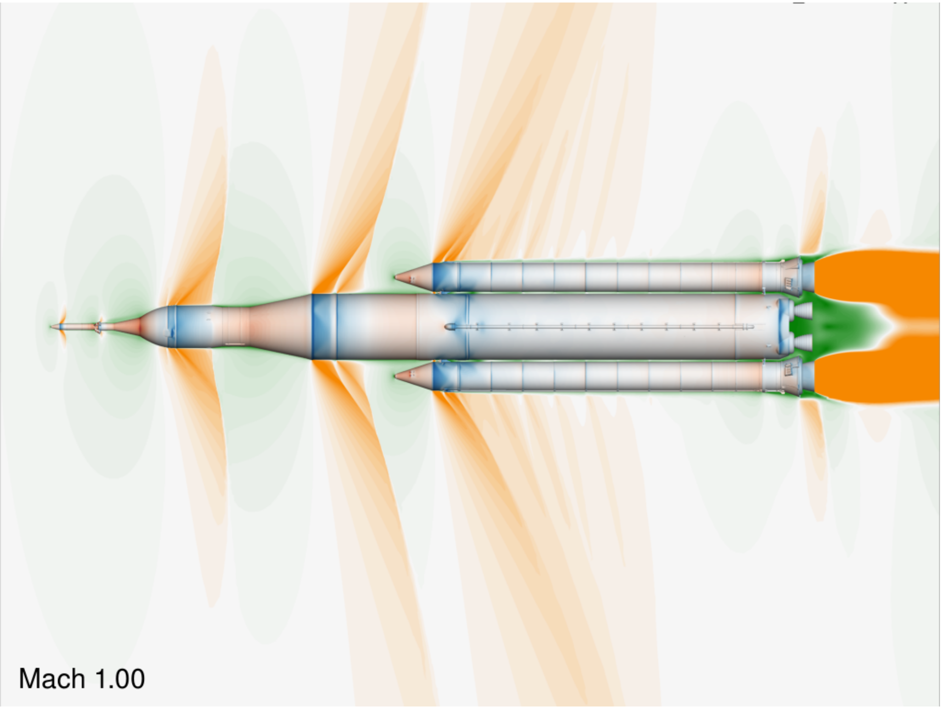
Mach 0.70

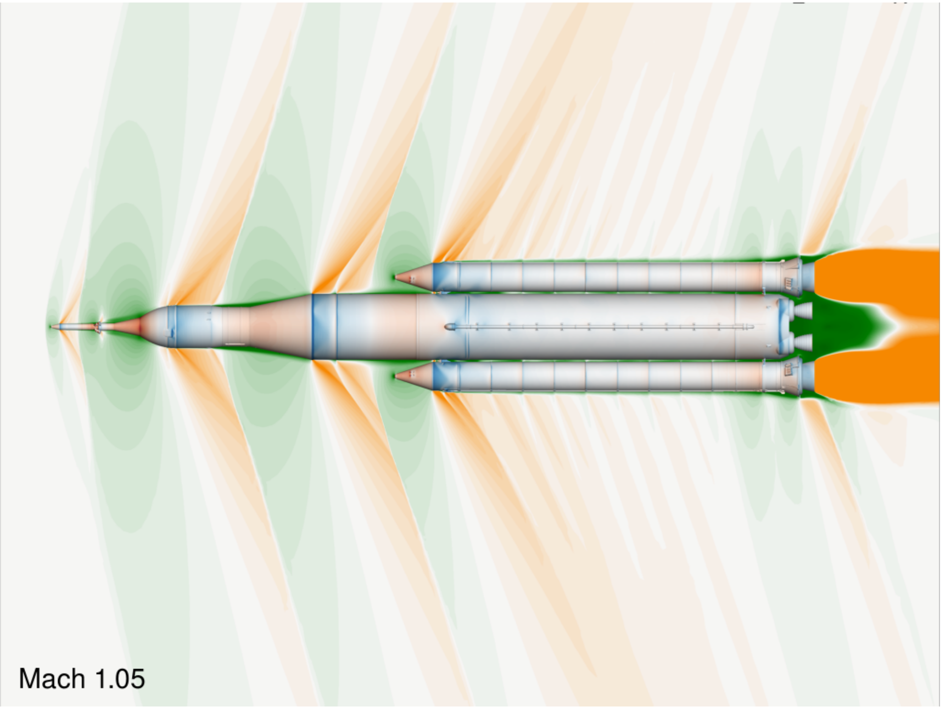

Mach 0.80

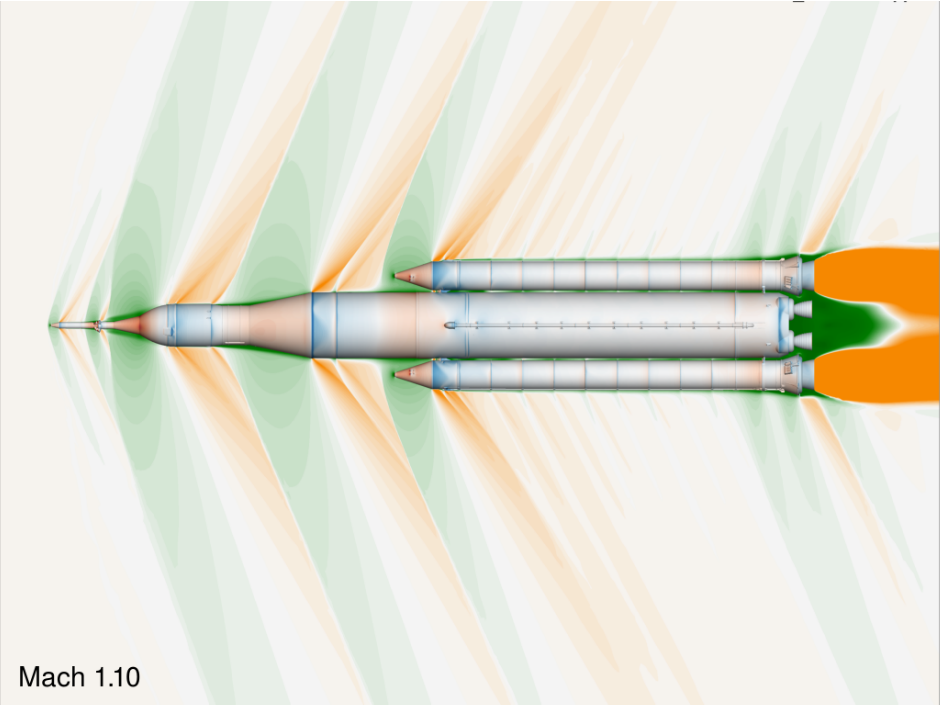

Mach 0.90

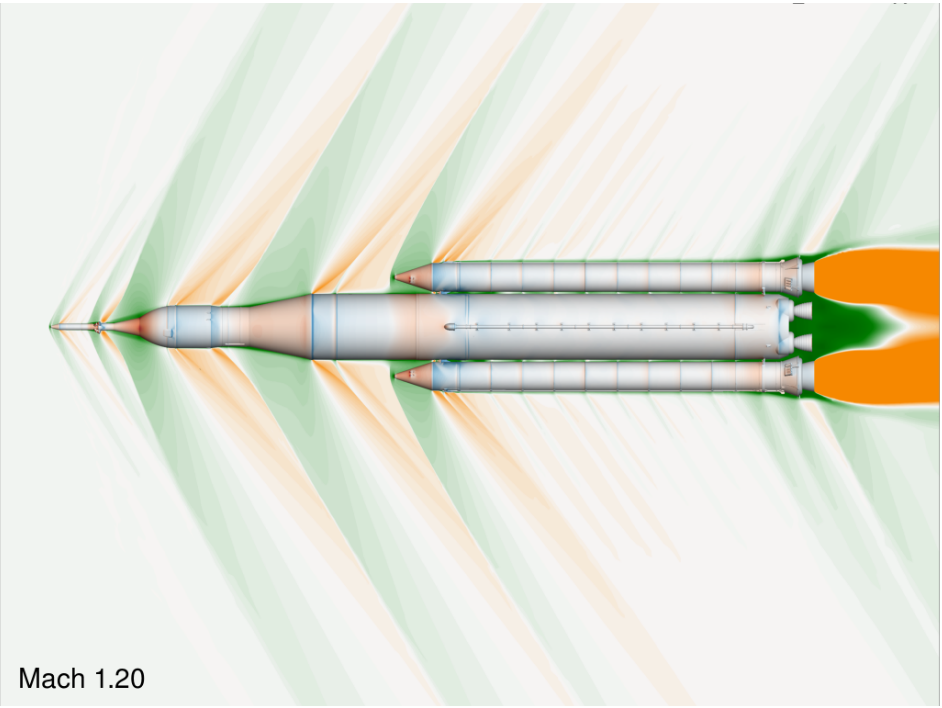

Mach 0.95


Mach 0.98

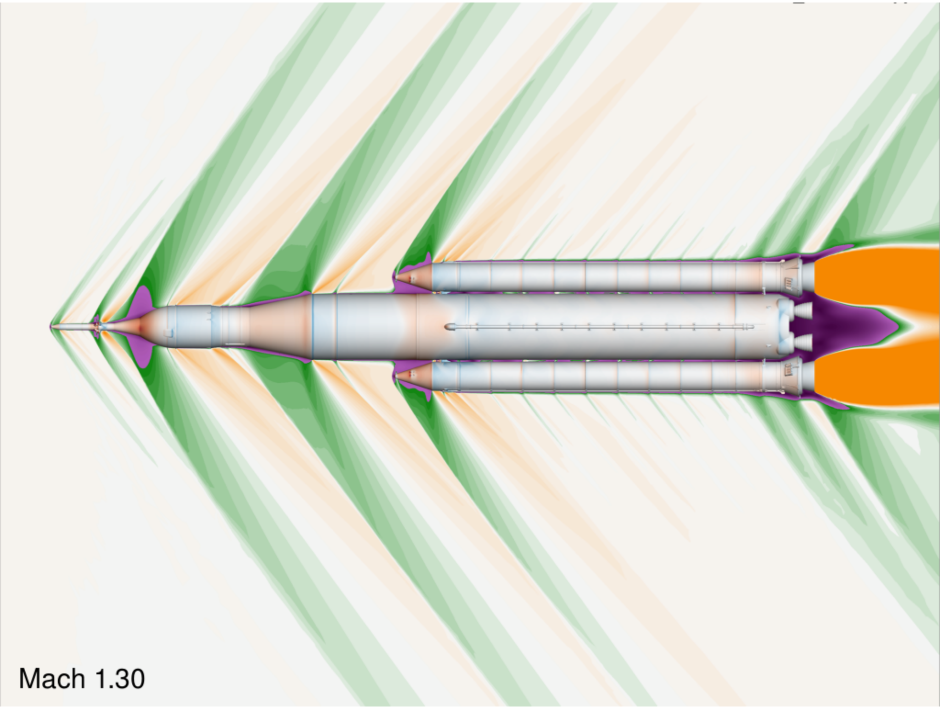

Mach 1.00

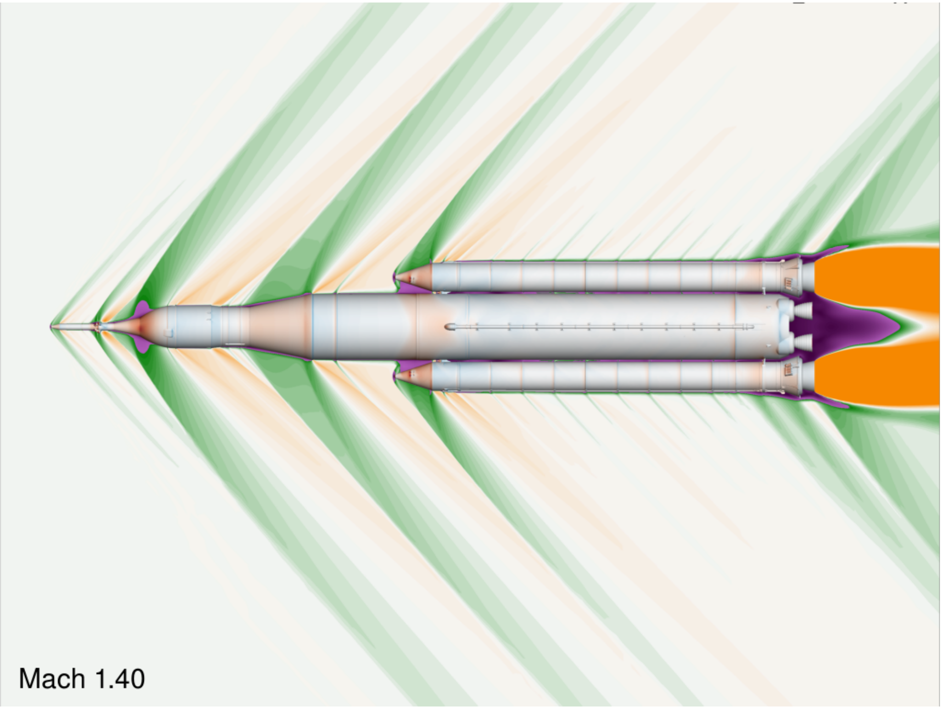

Mach 1.05

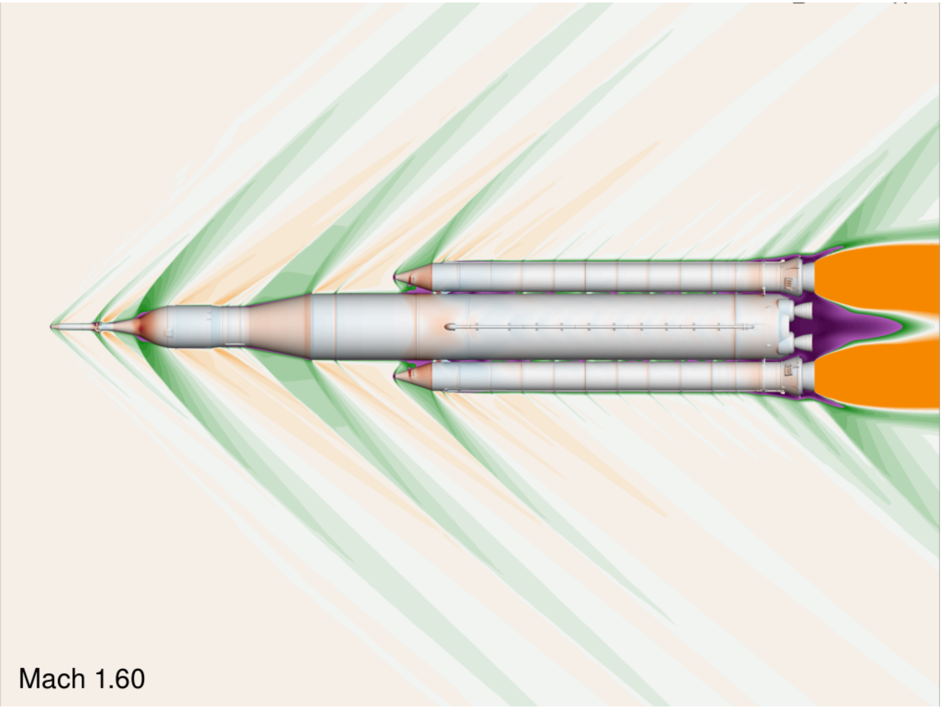

Mach 1.10

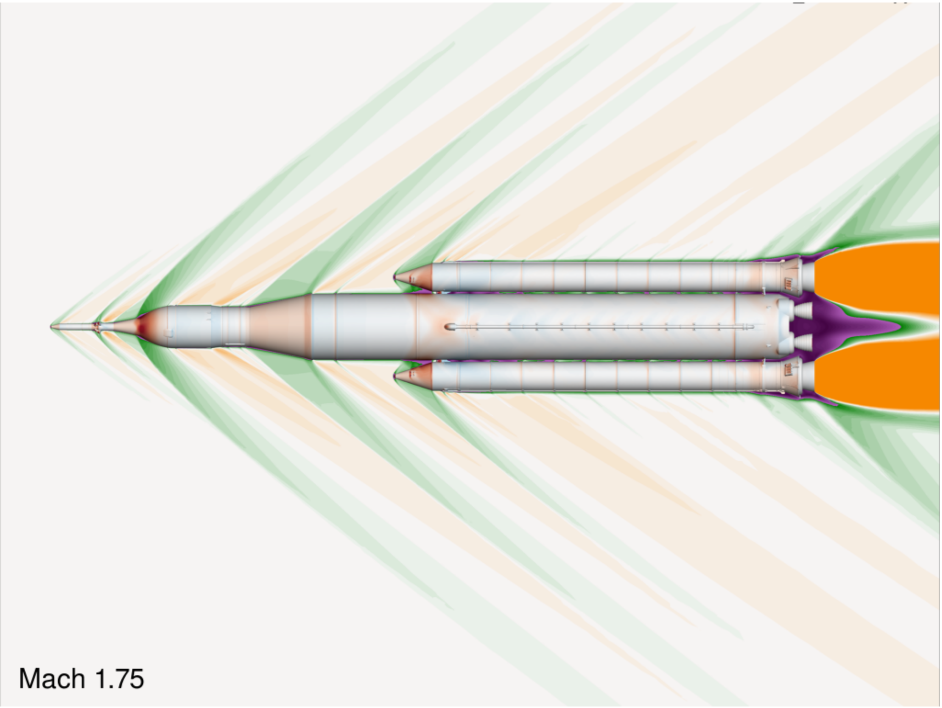


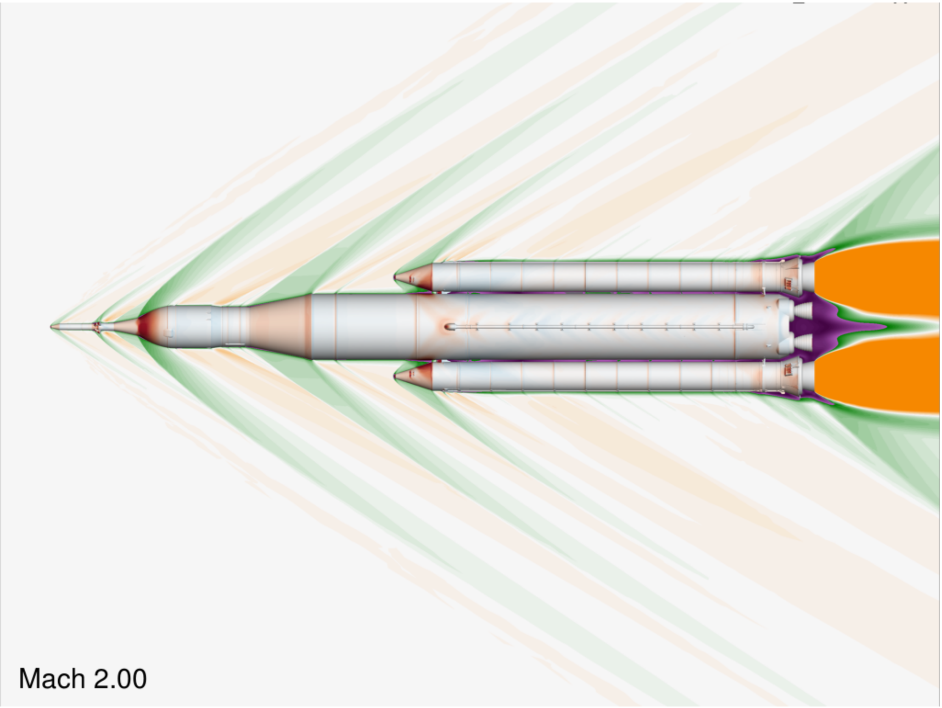
Mach 1.20

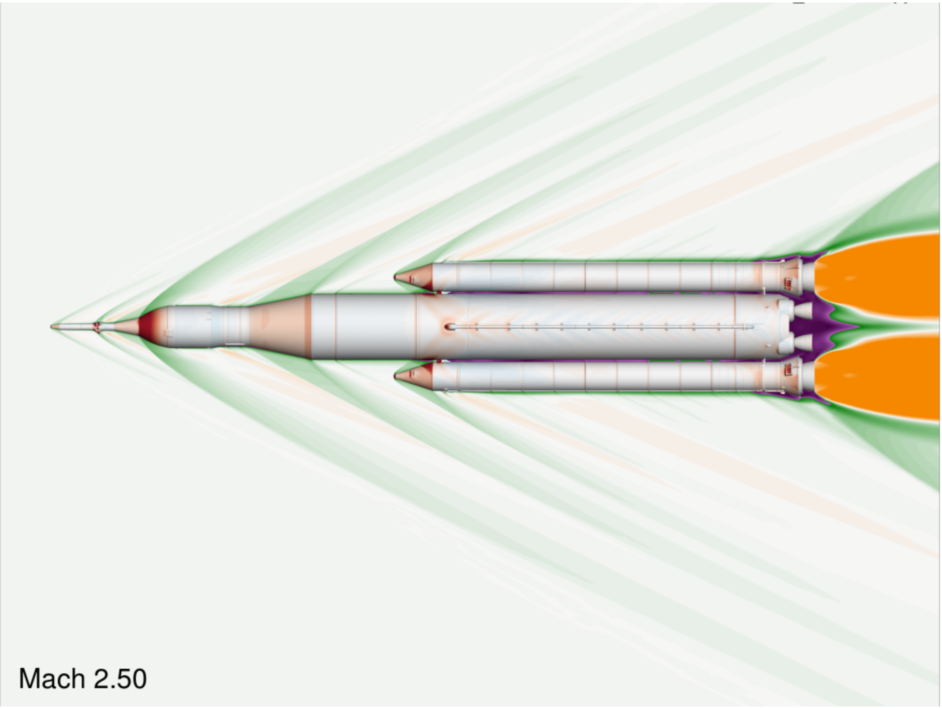

Mach 1.30

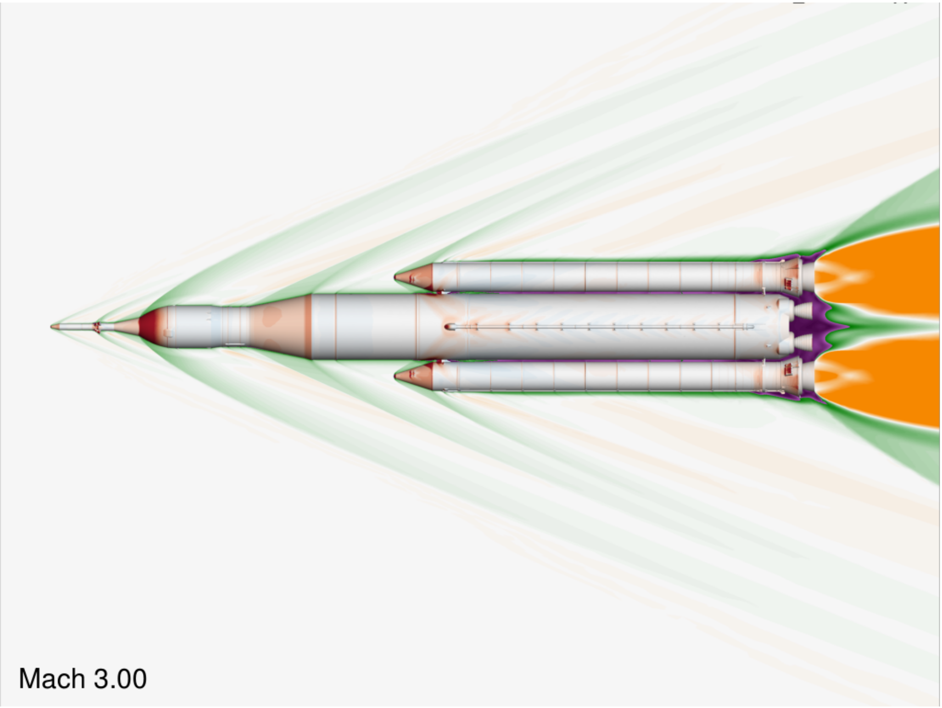

Mach 1.40

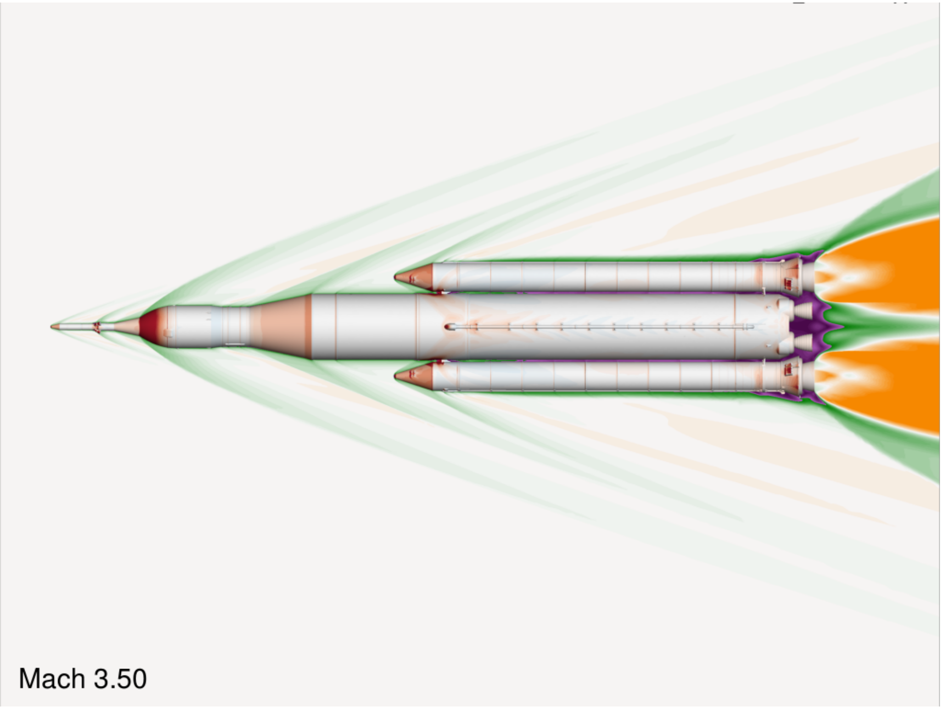

Mach 1.60

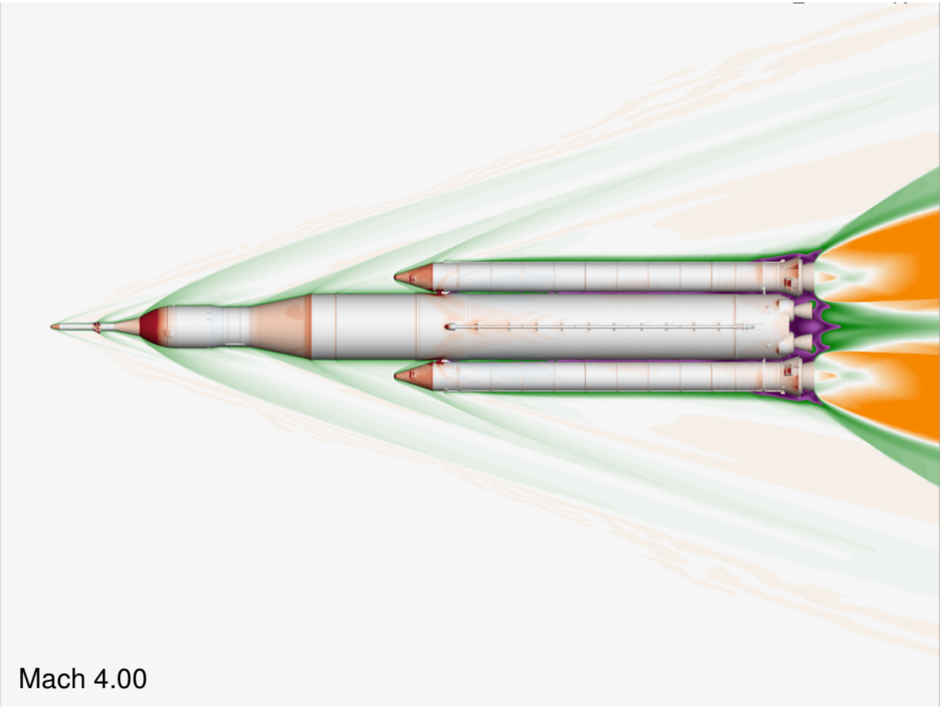

Mach 1.75


Mach 2.00

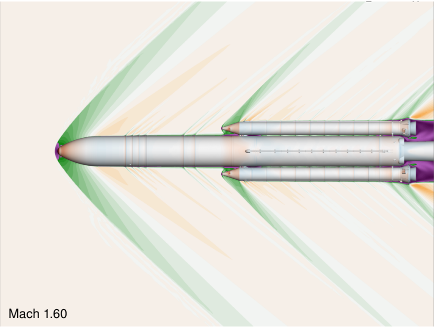

Mach 2.50


Mach 3.00


Mach 3.50


Mach 4.00

Forces & Moments



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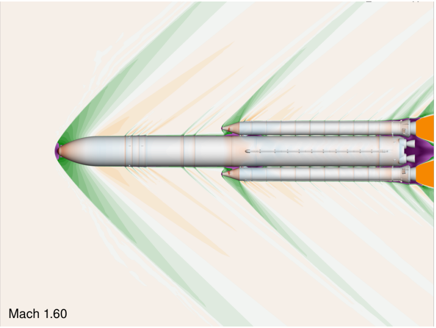
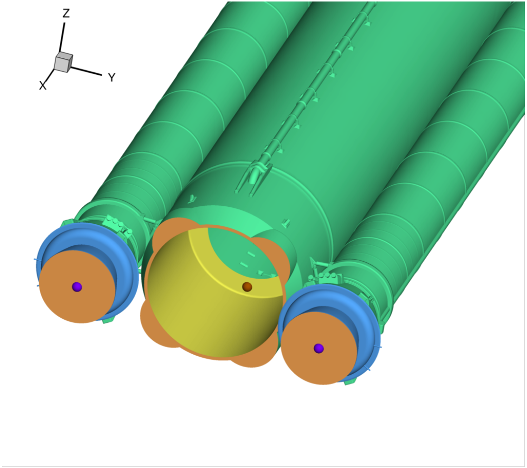


- Wind tunnel is more reliable (bounded error)
- The primary issue for a program like SLS is that some physical phenomena are missing (Reynolds number, geometric complexity, plumes, etc.)
- We're trying out a full CFD database of both the wind tunnel model and flight geometry as data sources for adjustment to F&M database
- **Important:** When modeling a wind tunnel test, really think hard about your assumptions and those that went into the test

Measuring Forces: Subtract from Metric Component

Subtract base pressure times area for CORE, LSRB, RSRB



Integration Surfaces

- ● – 4 cavity C_p taps
- ● – LSRB/RSRB C_p taps
- ● – 4 sting C_p taps
- ● – alt. sting taps

Mimic Base Correction

$C?F$: `STACK_Mimic`
$CL?F$: `STACK_Mimic`

Core Base Pressure

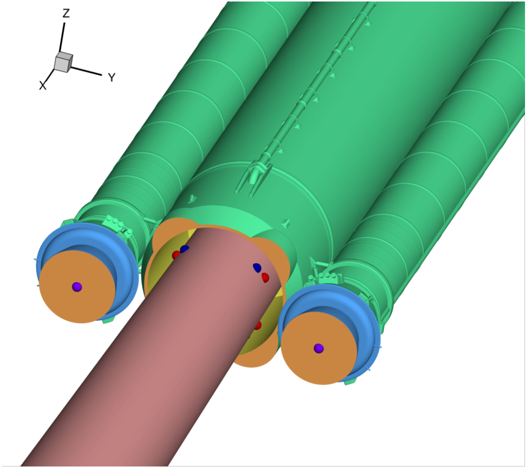
$$C_{p,CORE} = \frac{1}{4}\left(C_{p,\mathtt{St005}} + C_{p,\mathtt{St006}} + C_{p,\mathtt{St007}} + C_{p,\mathtt{St008}}\right)$$

Combinations

$$\mathtt{STACK\_Total} = \mathtt{STACK\_Metric} + C_{p,cavity} A_{sting}$$
$$\mathtt{STACK\_Mimic} = \mathtt{STACK\_Total} - C_{p,CORE} A_{CORE} - C_{p,LSRB} A_{LSRB} - C_{p,RSRB} A_{RSRB}$$

Measuring Forces: Subtract from Metric Component

Subtract base pressure times area for CORE, LSRB, RSRB



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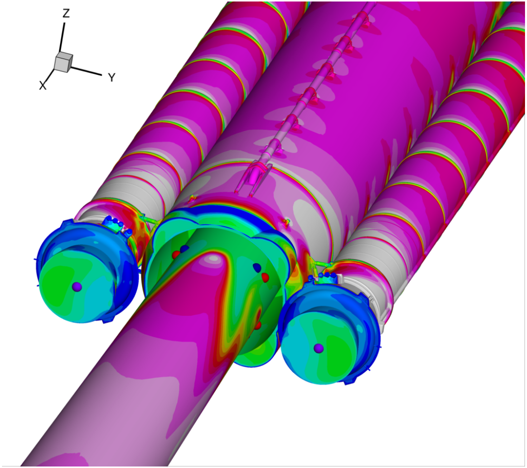
Measuring Forces: Subtract from Metric Component

Can be different from integrating forebody directly!



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Core Base Pressure

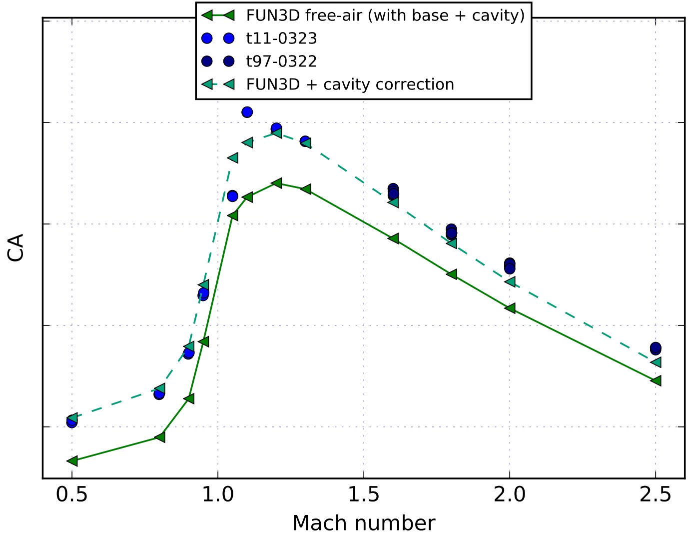
$$C_{p,CORE} = \frac{1}{4}\left(C_{p,\mathtt{St005}} + C_{p,\mathtt{St006}} + C_{p,\mathtt{St007}} + C_{p,\mathtt{St008}}\right)$$

Notes

The SRB nozzle base and SRB "skirt" base have different pressures

Communicate with the test team what the detailed intentions are

Effects on Axial Force (*CA*)

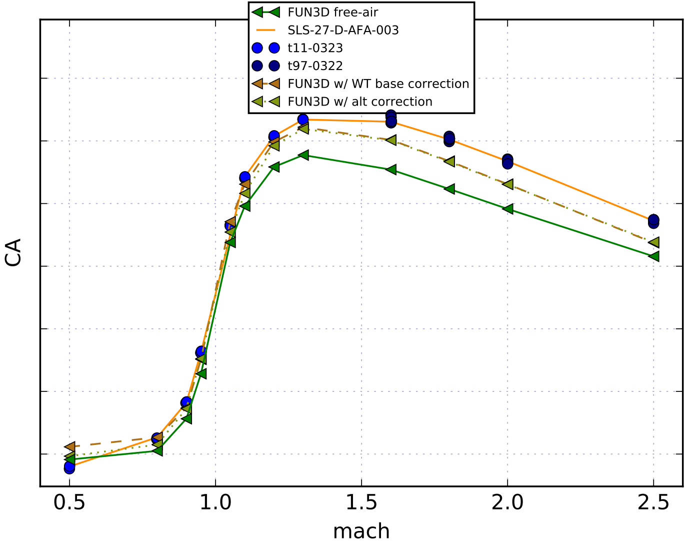


Applying the cavity pressure to the area of the sting cross section gives results quite close to *uncorrected* raw wind tunnel measurement

There are difficulties at Mach 1.05 and 1.10; walls may be important here

Mach sweep of raw axial force at $\alpha = -2^\circ$, $\beta = 0^\circ$

Effects on Axial Force (CA)

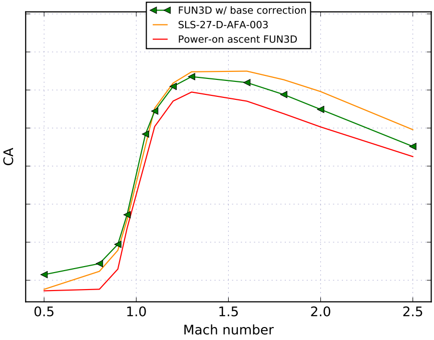


Mimicking the base-correction technique in the wind tunnel (dashed lines) gets much closer to wind tunnel database (orange line) results than direct integration (green line)

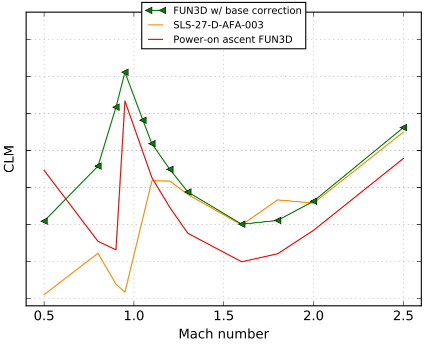
Not too sensitive to base pressure sensor location (dashed vs dotted)

Mach sweep of "forebody" axial force at $\alpha = -2^\circ$, $\beta = 0^\circ$

Wind Tunnel-to-Flight Adjustment Samples



Axial force coefficient (CA)



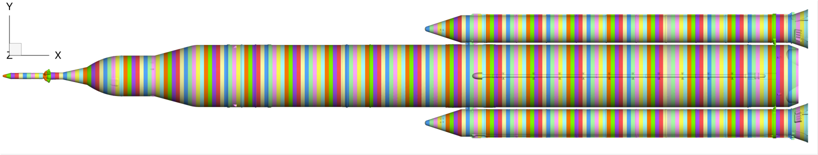
Pitching moment (CLM) about c.g.

- Adjusted database would be *orange* + (*red* − *green*)
- Difference in drag could mean a few hundred extra pounds to orbit
- Effect of plumes makes the vehicle slightly more unstable
- This scheme would still allow wind tunnel results to take precedence where there is a disagreement (i.e. *green* vs. *orange*)

Sectional Loads/Line Loads

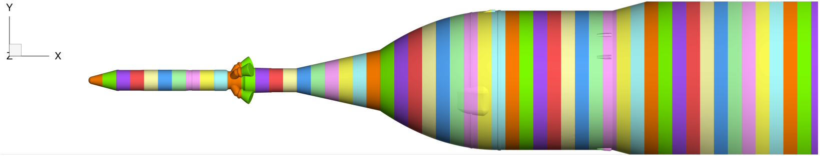
Aero inputs for large-scale (static) structural analysis

- **Divide the vehicle into slices**



Block 1B Crew Configuration divided into 200 axial slices

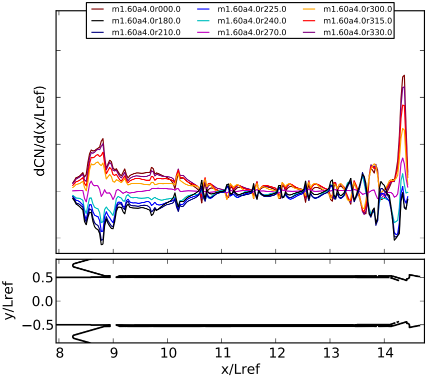
- Calculate the load on each slice
- Record as $\Delta C_N / \Delta(x/L_{ref})$



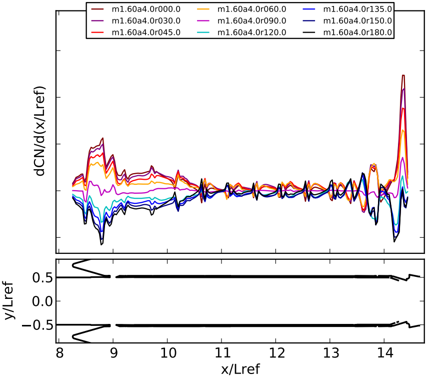
Zoomed in on the forward slices

Sample Line Loads from SLS Block 1

Block 1 Line Loads at Mach 1.60, $\alpha_t = 4^\circ$



LSRB/*CN*, $\beta \leq 0^\circ$



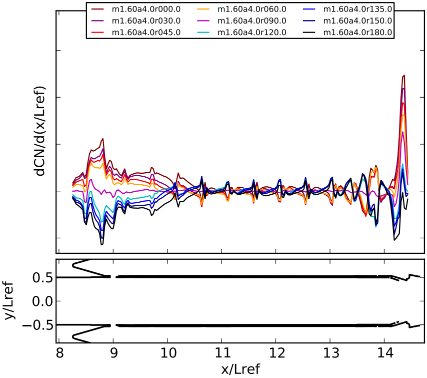
RSRB/*CN*, $\beta \geq 0^\circ$

Checks at each Mach number

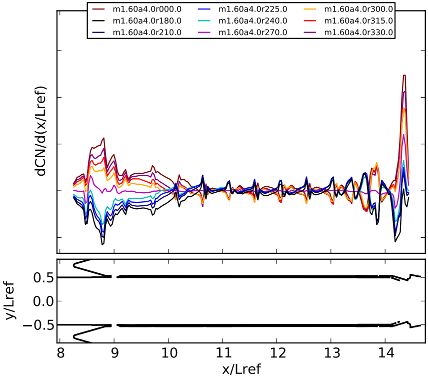
- Take all (16) cases from the edge of the flight envelope
- Split them in half and plot each
- Check for expected symmetries

Sample Line Loads from SLS Block 1

Block 1 Line Loads at Mach 1.60, $\alpha_t = 4^\circ$



LSRB/*CN*, $\beta \geq 0^\circ$



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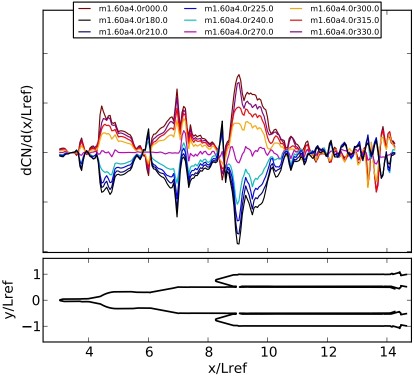
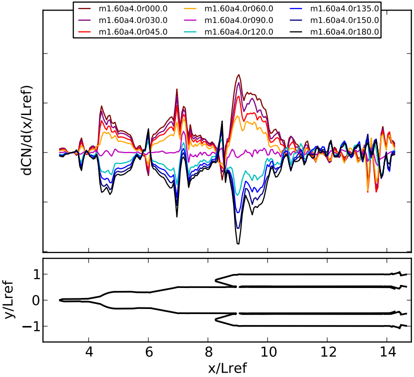


CORE/*CN*, $\beta \leq 0^\circ$



CORE/*CN*, $\beta \geq 0^\circ$

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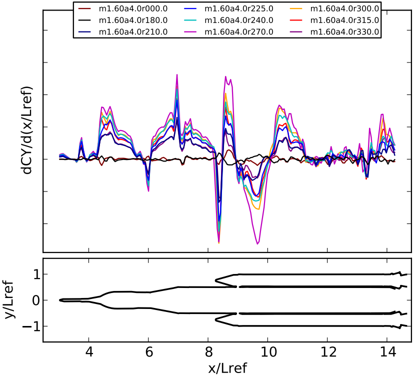
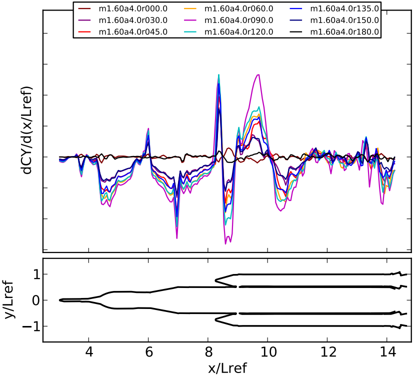


CORE/*CY*, $\beta \leq 0^\circ$

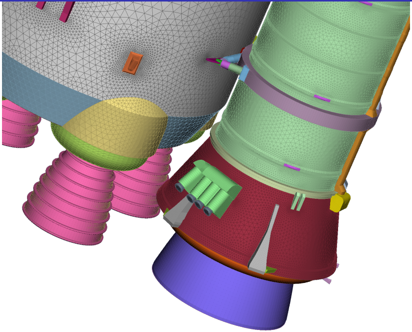


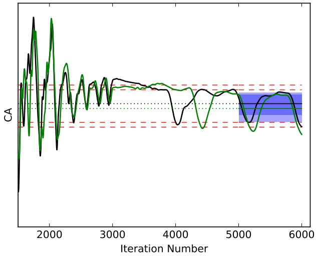
CORE/*CY*, $\beta \geq 0^\circ$

Checks at each Mach number

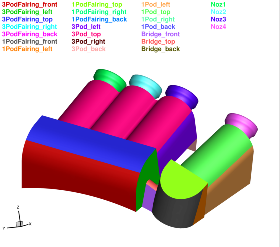
- Take all (16) cases from the edge of the flight envelope
- Split them in half and plot each
- Check for expected symmetries

PAL Example: SRB Aft Booster Separation Motor Pod

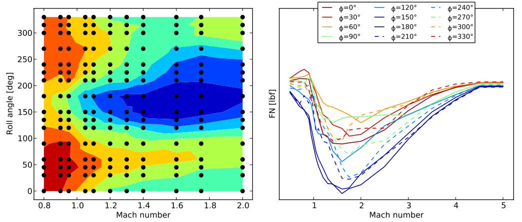




Check iterative convergence



Loads on each patch



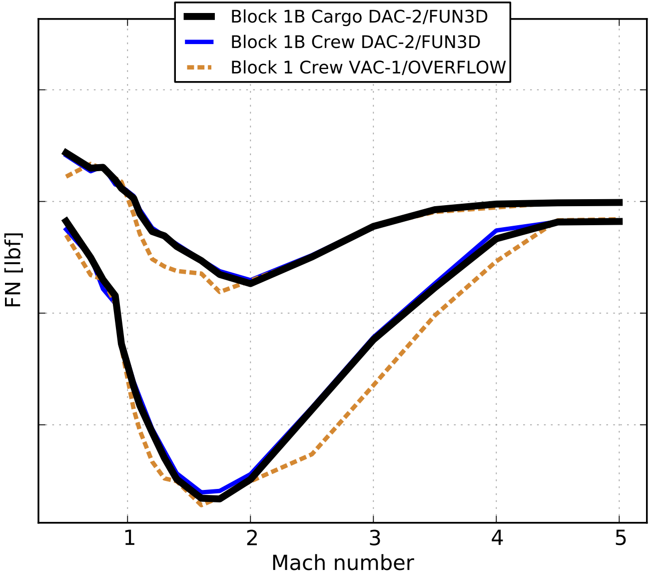
Attempt to make meaningful plots

Protuberance Air Load Plots: Mach Envelope

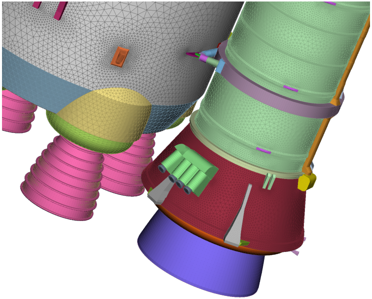
Summary of forces on a family of protuberances with the same structure

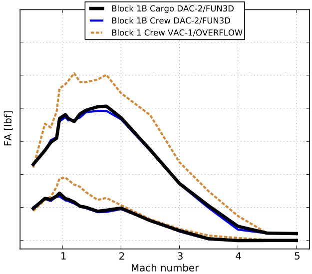
Calculate the minimum and maximum force (in lbf) at each Mach number from any combination of angle of attack and sideslip

Quick summary; allows comparisons of different vehicles

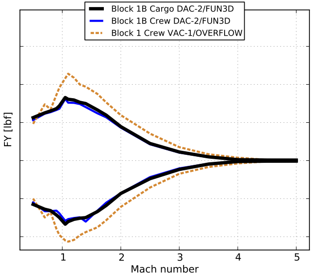


Protuberance Plots: Aft BSM Pods

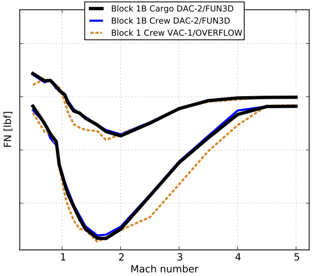




Axial force: *CA*

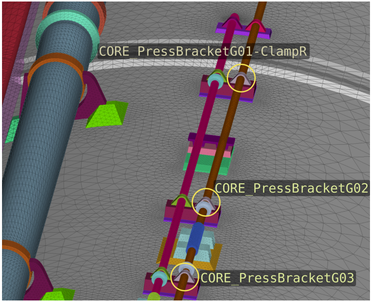


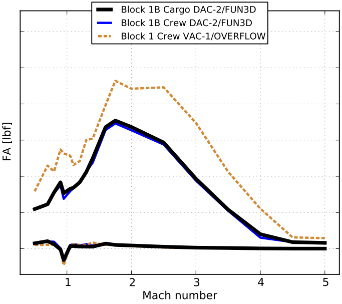
Side force: *CY*

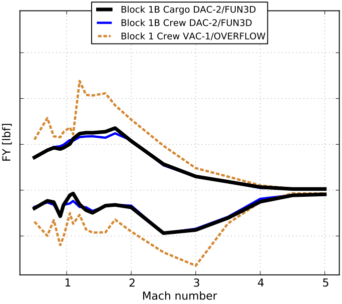


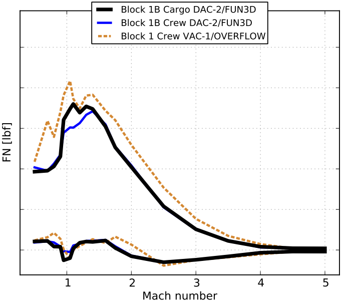
Inward/outward force: *CN*

Protuberance Plots: Pressurization Line Brackets

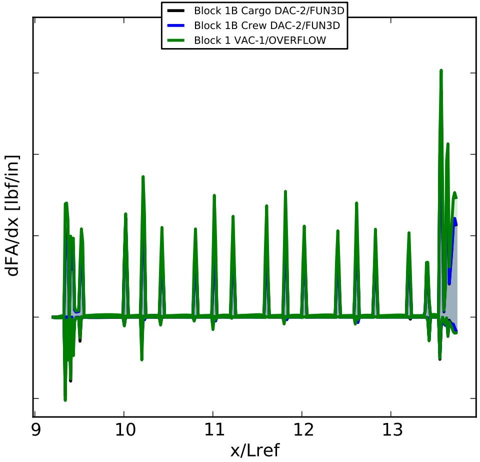




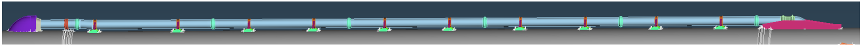




Protuberance Line Loads



- Divide thin protuberances (fuel lines, systems tunnels, etc.) into slices and calculate the loads on each slice
- To create a structural envelope, take the min and max sectional load (in lbf per inch) from 750+ simulations
- This example is from liquid oxygen feed line on the top of the vehicle, showing axial force



Booster Separation — A Lot

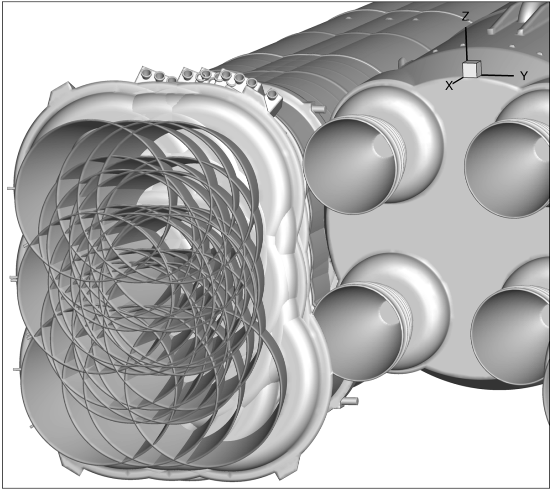
8-dimensional run matrix:

Variable	Description
Δx	SRB axial translation
Δy	SRB outward translation
Δz	SRB vertical translation
$\Delta\psi$	SRB yaw (rel. to core)
$\Delta\theta$	SRB pitch
α	CORE angle of attack
β	CORE sideslip angle
$C_{T,BSM}$	BSM thrust coefficient

Other variables held constant:

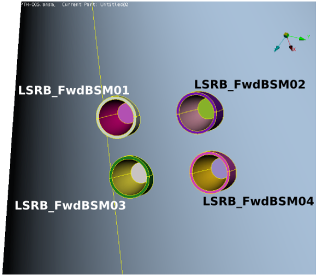
Variable	Description
$\Delta\phi$	SRB roll
M_∞	CORE Mach number
$C_{T,CSE}$	CORE engine thrust
$C_{T,SRB}$	SRB thrust

Full run matrix: $\sim$15k cases

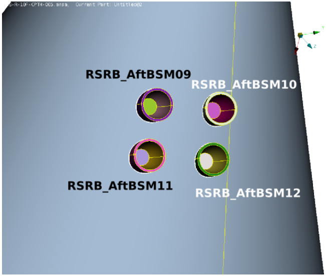


All SRB positions simulated at $\Delta x = 6$ ft... Each pos. has 3-var run matrix (α,β,C_{TBSM})

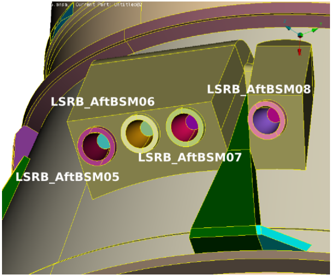
BSM: 16 Booster Separation Motors



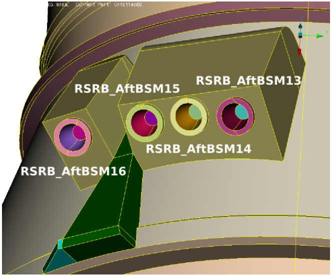
LSRB Forward BSMs



RSRB Forward BSMs

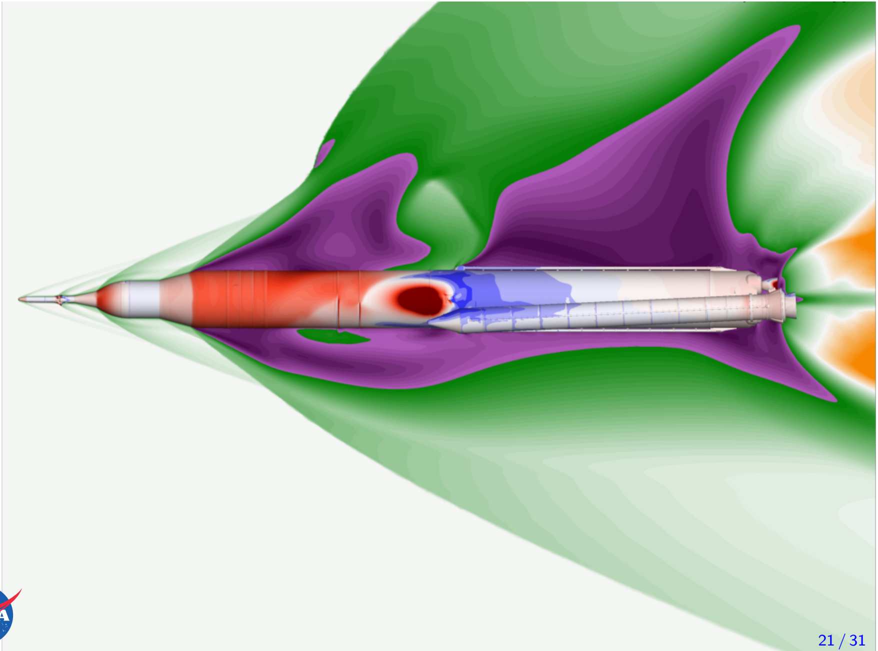


LSRB Aft BSMs

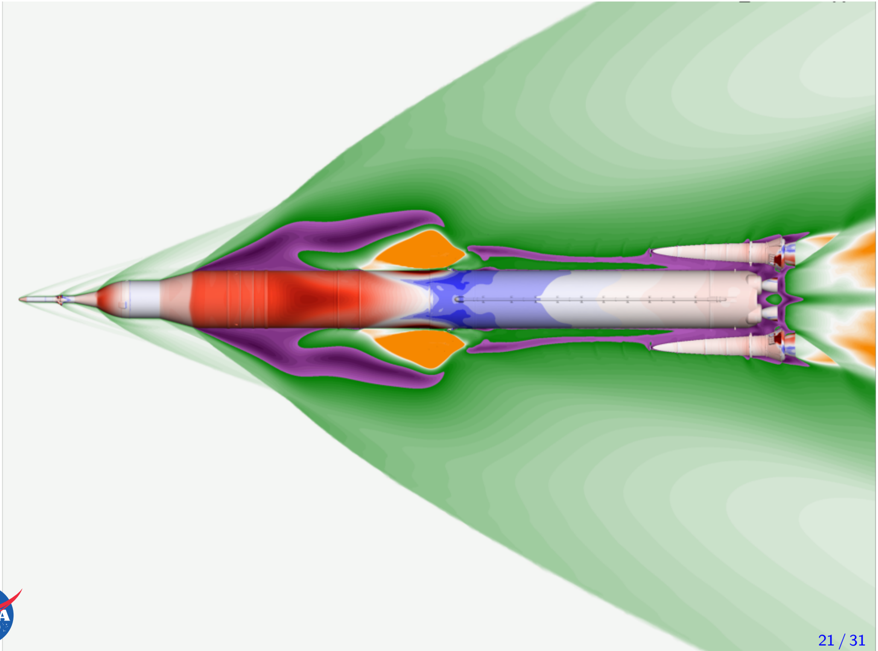


RSRB Aft BSMs

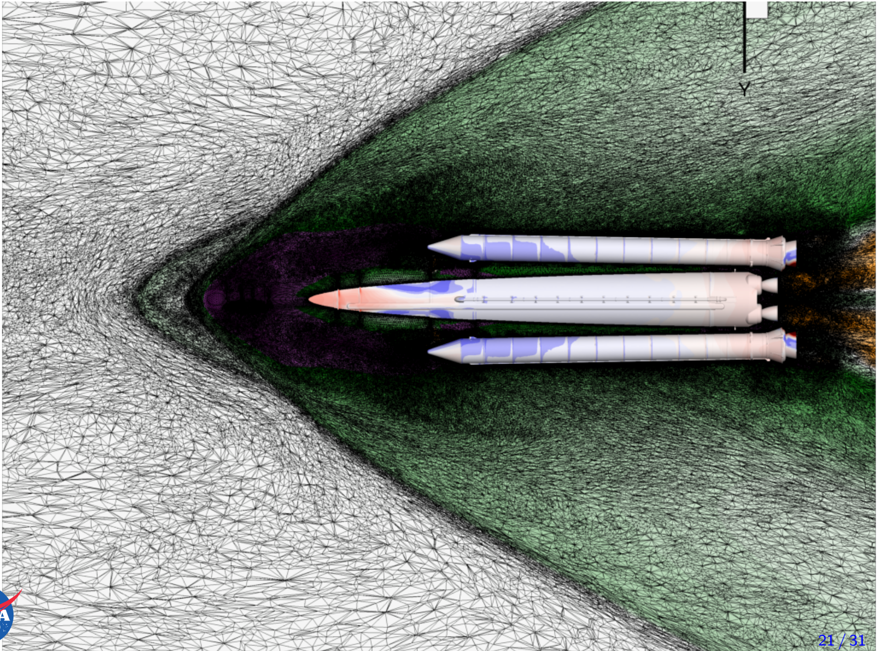
Booster Separation Flow



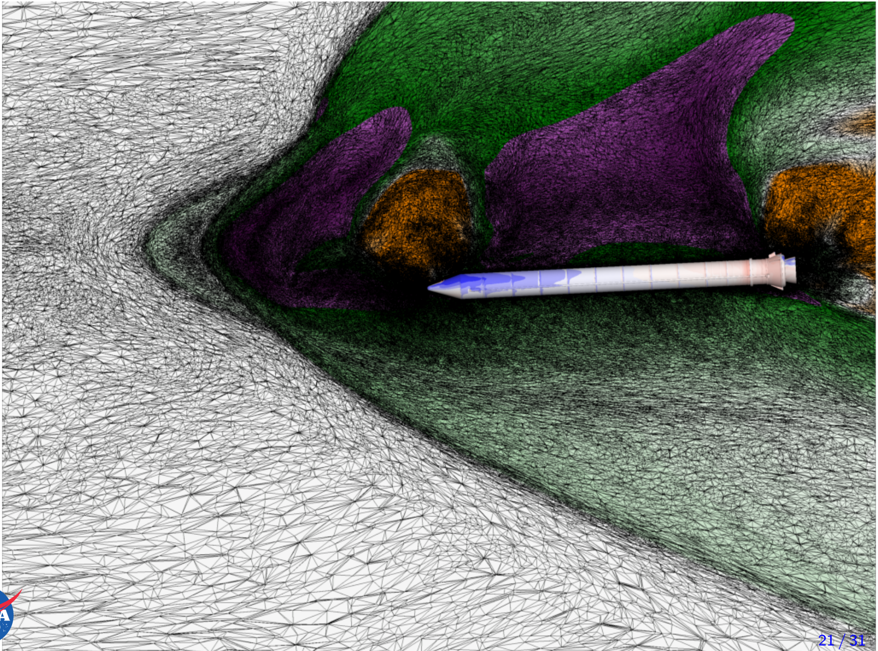
Booster Separation Flow



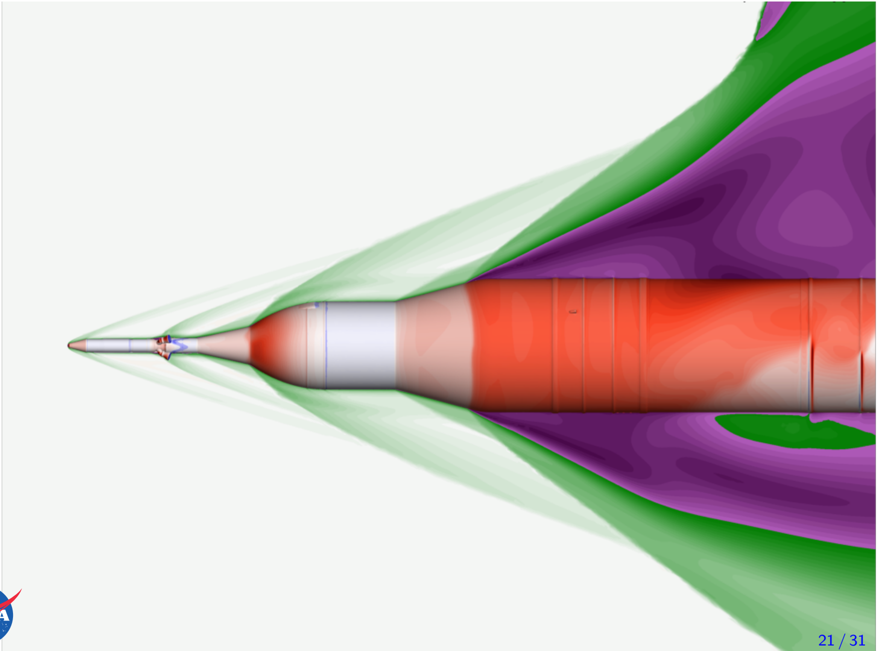
Booster Separation Flow



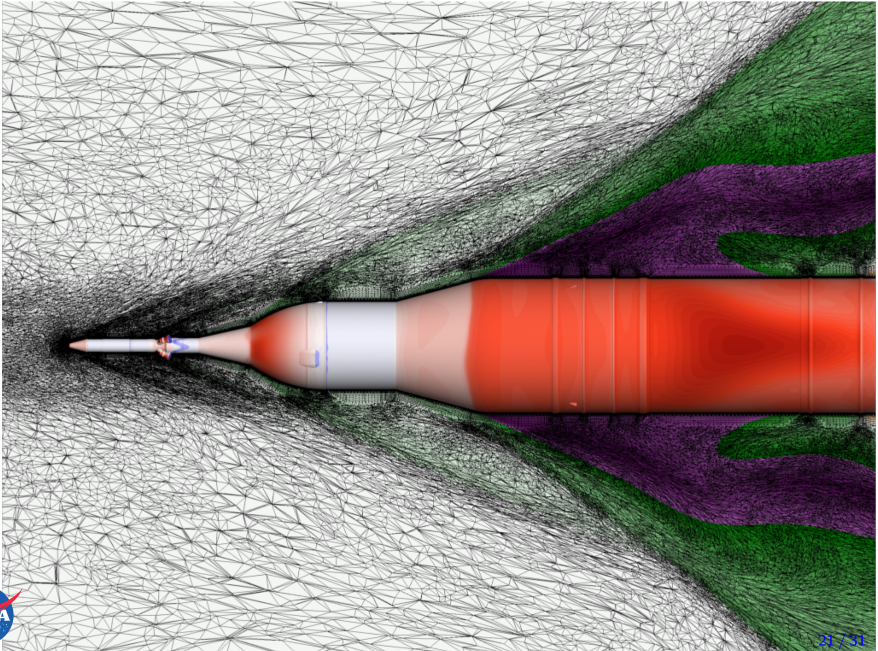
Booster Separation Flow



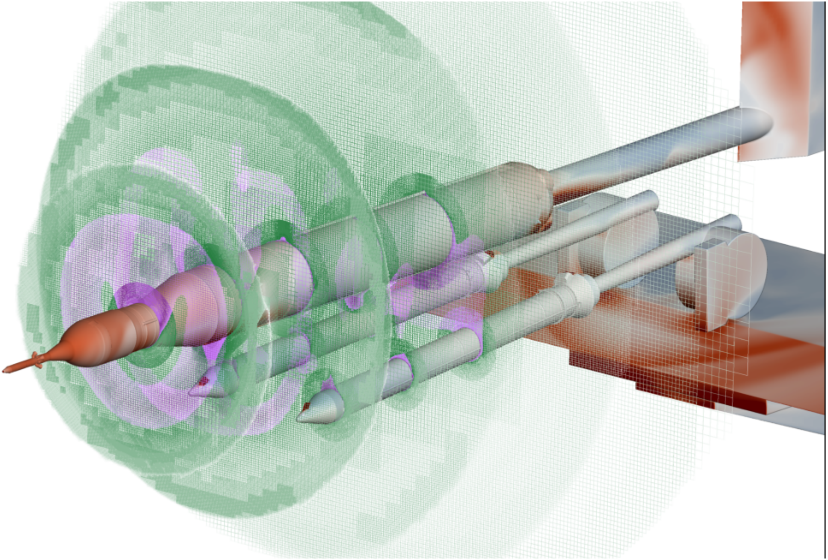
Booster Separation Flow



Booster Separation Flow

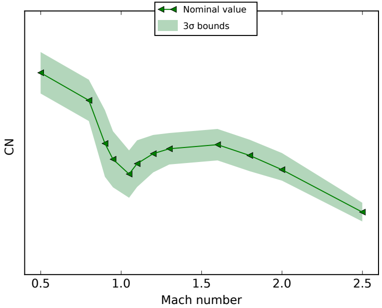


Booster Separation Flow

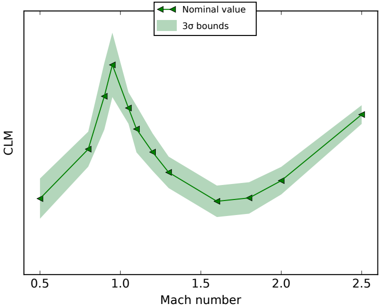


Example of Unintended UQ Consequences: x_{cp}

Some cartoons of CN and CLM with reasonable 3σ bounds:



Normal force Mach sweep



Pitching moment Mach sweep

Center of Pressure (x_{cp})

A naïve approach, uncertainty in x_{cp} depends on the **M**oment **R**eference **P**oint:

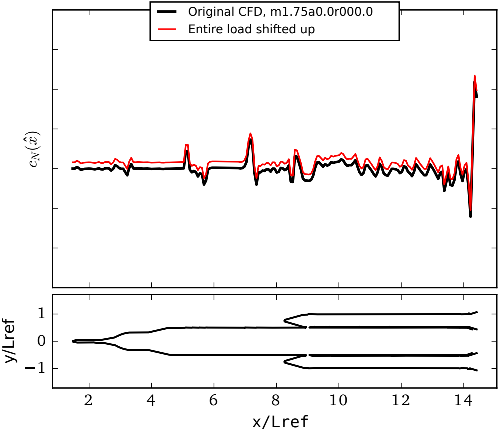
$$\frac{x_{cp}}{L_{ref}} = \frac{x_{MRP}}{L_{ref}} - \frac{C_m}{C_N} \qquad \frac{\sigma_{xcp}}{L_{ref}} = \frac{1}{C_N}\sqrt{\sigma^2_{CLM} + \frac{C_m^2}{C_N^2}\sigma^2_{CN}}$$

Pretty easily σ_{xcp} can exceed length of the vehicle!

1D UQ Example: Line Loads

Applying UQ to a multidimensional database is more challenging

Consider what happens when you just add a delta to the whole load:



Nomenclature

Scaled axial coordinate:

$$\hat{x} = x/L_{ref}$$

Original CFD load:

$$c_N(\hat{x})$$

Perturbed load:

$$\hat{c}_N(\hat{x}) = c_N(\hat{x}) + \delta\hat{c}_N(\hat{x})$$

Bad ideas

Constant offset:

$$\delta\hat{c}_N(\hat{x}) = \varepsilon$$

Scaled offset:

$$\delta\hat{c}_N(\hat{x}) = \varepsilon c_N(\hat{x})$$

- Some regions are easier to predict than others
- Quite often the sectional load is zero for a reason
- What happens to integrated *CN* and *CLM*?

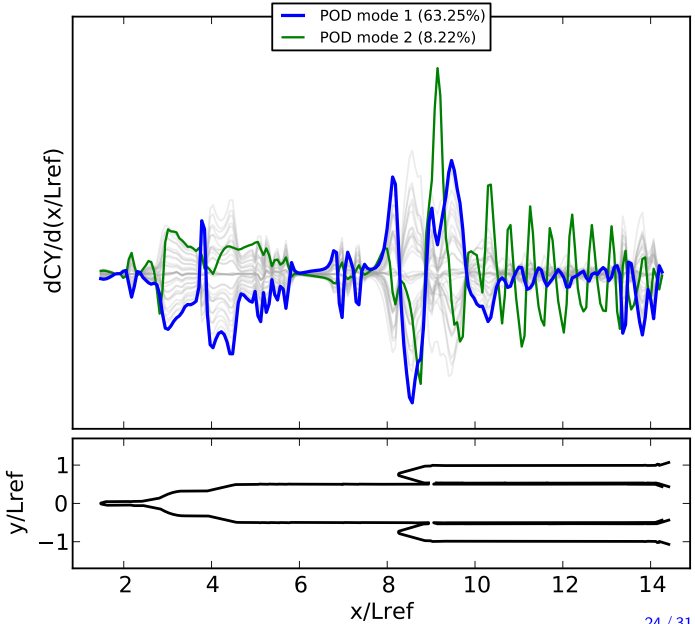
Idea: Use the Other Line Loads As Candidate “Shapes”

Gray lines are the raw CFD line loads from all Mach 1.3 solutions

Blue line is the first candidate shape function; looks like one of the other line loads

Green line is the second mode; has a little different profile

Use ∼10 modes and a method to pick a linear combination



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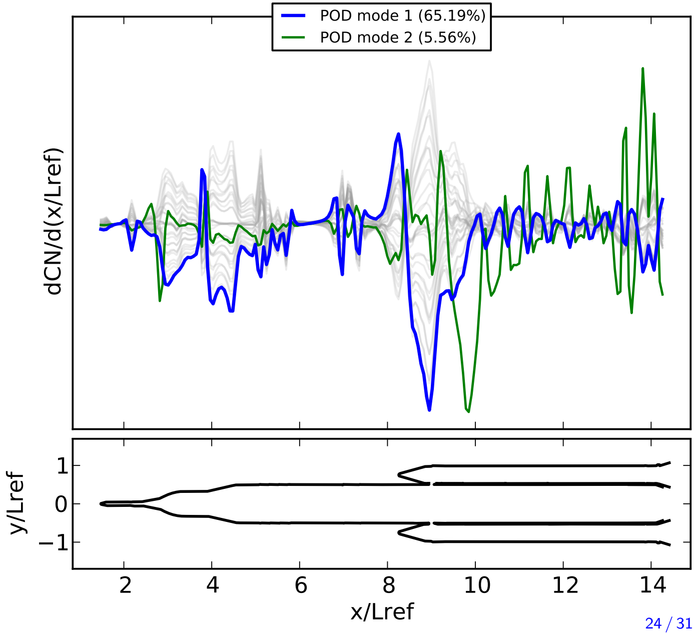

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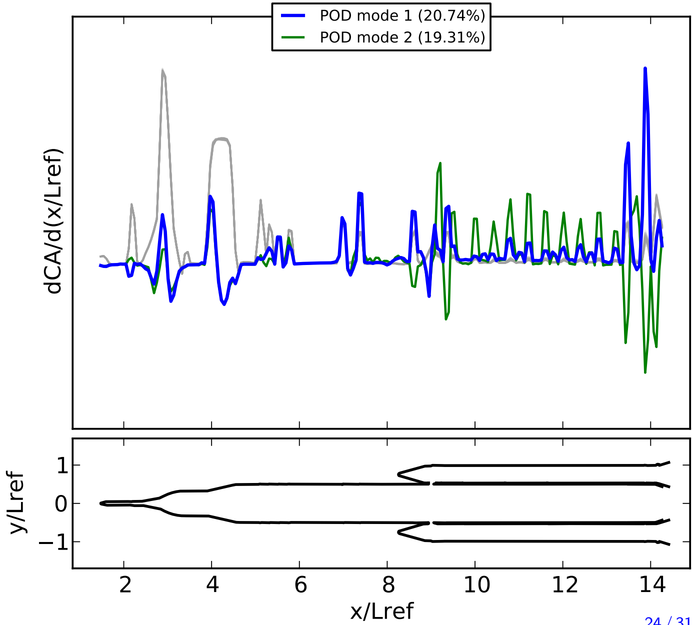


Principles of Dispersed Line Loads

- Have the line load uncertainty be mostly inherited from the force & moment uncertainty
- That is, $\delta c_N(\hat{x})$ is constructed in order to hit target overall values of C_N and C_m, which are governed by random draws
- Let $c_N(\hat{x})$ be the nominal line load at conditions (M, α, β) that produces the largest bending load on the vehicle
- This $c_N(\hat{x})$ is consistent with $C_N(M, \alpha, \beta)$ and $C_m(M, \alpha, \beta)$, which is smaller than $C_N + 3\sigma_{CN}$ and $C_m + 3\sigma_{CLM}$, might have a smaller bending moment

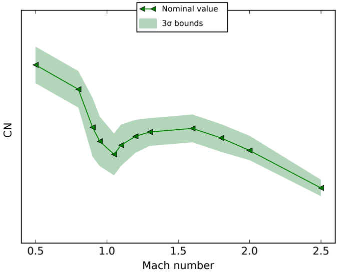
- There are simpler ways of addressing this potential lack of conservatism

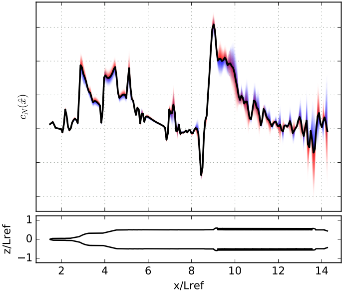
- This technique doesn't cover all possible line loads
- It is deterministic in that

$$(M, \alpha, \beta, \varepsilon_{CN}, \varepsilon_{CLM}) \to \hat{c}_N(\hat{x})$$

- We can add other choices for $\delta c_N(\hat{x})$ that don't affect the integrated loads and add them (pseudo-)randomly

Principles of Dispersed Line Loads





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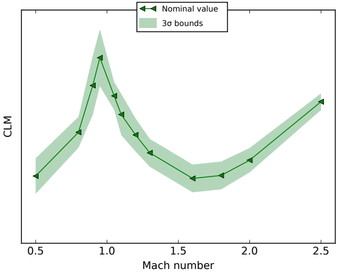
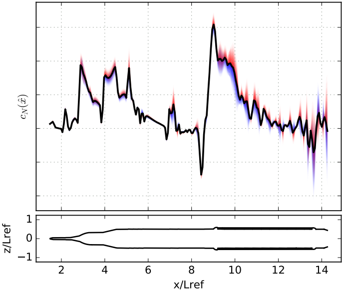
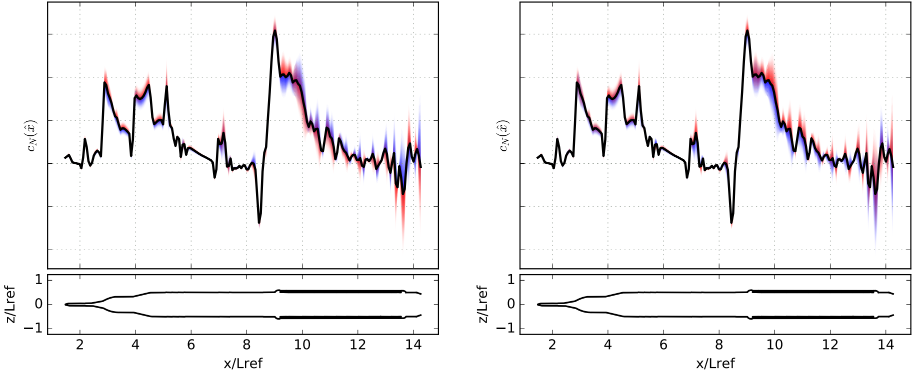




Example C_N Dispersed Load at Mach 1.75, $\alpha = 4^\circ$, $\beta = 0^\circ$

Plot same set of dispersed line loads two different ways:



Colored by ε_{CN} Colored by ε_{CLM}

- Blue/red areas are sections that correlate with integrated C_N or C_m
- Purple areas indicate the opposite
- Some sections have almost no dispersion
- Some regions are "flipped", e.g. increasing C_N decreases local load

Example Dispersed Load at Mach 1.75, $\alpha = 4^\circ$, $\beta = 0^\circ$

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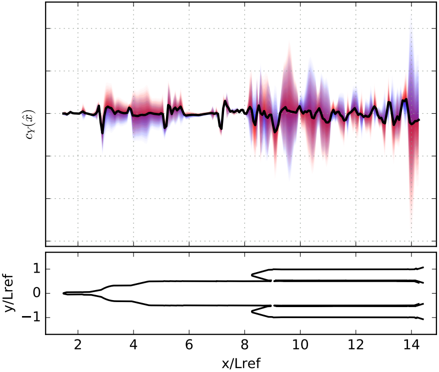
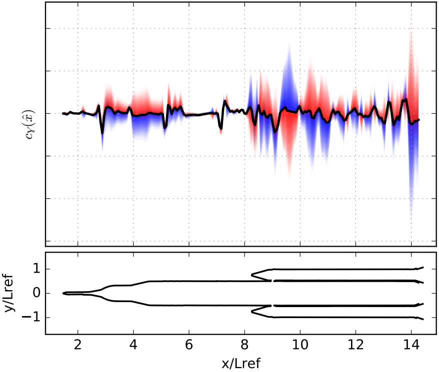


Colored by ε_{CY}



Colored by ε_{CLN}

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Database Tools

Running

Example: set up and submit 10 OVERFLOW jobs at Mach 1.75

```
$ pyover --re m1.75 -n 10
```

Generate report

Example: generate LaTeX report for cases 79 and 402

```
$ pycart -I 79,402 --report
```

Checking status

Example: Check status of FUN3D jobs at Mach 1.75

```
$ pyfun --re m1.75 -c
Case Config/Run Directory       Status  Iterations  Que CPU Time
---- ----------------------- ------- ----------- --- --------
81   poweron/m1.75a0.0r000.0 RUNNING 4237/5000   R    11273.7
82   poweron/m1.75a4.0r000.0 QUEUE   3000/4000   Q     2633.1
83   poweron/m1.75a4.0r090.0 PASS    5000/5000   .    10743.3

PASS=1, RUNNING=1, QUEUE=1,
```

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```

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```
$ pycart -I 79,402 --report
```

Collect forces and moments

Example: update F&M database for high-ϕ cases

```
$ pyfun --cons "phi>180" --aero
```

Extract protuberance air loads

Example: get patch loads for components starting with "M"

```
$ pyover --triqfm "M*"
```

Collect line loads

Example: generate line loads for Mach 2.0 cases, $2 \le \alpha_t < 7$

```
$ pyfun --ll --re 2.00a[2-6]
```

Archiving

Example: create backup and delete large files from working copy

```
$ pyover --archive
```

Derek's Guidelines for CFD Aero Database Work

- Do not blindly follow instructions from project managers or task requesters; they are expecting your expert opinions on the nature of the questions being asked—not just to provide data
- Always create a tool to partially automate setup, run procedure, and post-processing
- Look at every case individually before accepting it
- Try to plot every item in the database
- Plot every type of data in the database at least two ways
- Document the process used and make it accessible to customers
- Contact your customer if you can

Comments about UQ for Launch Vehicles

- It can be difficult to get appropriate early estimates of uncertainty. There's a curious result that uncertainties often *grow* as the database gets more mature
- Uncertainties are often as important as the nominal values for a launch vehicle
- Try to understand beforehand how the uncertainty will be used by the customer
- Don't introduce uncertainties that have non-physical consequences

Acknowledgments

- Members of the NASA ARC/TNA SLS CFD Team:
  - Stuart Rogers
  - Jeff Onufer
  - Henry Lee
  - Jamie Meeroff
  - Tom Pulliam
  - and many previous members
- NASA Advanced Supercomputing facilities (a *lot* of SBUs)
- SLS Program; this work is part of the SLS Aero Task Team
- Human Explorations & Operations Mission Directorate (HEOMD)
- NASA Engineering & Safety Center (NESC) for discussions and reviews